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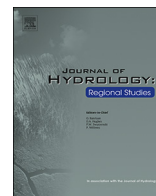
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Assessing potential winter weather response to climate change and implications for tourism in the U.S. Great Lakes and Midwest

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ABSTRACT

Study Region: Eight U.S. states bordering the North American Laurentian Great Lakes.

Study Focus: Variable Infiltration Capacity (VIC) model simulations, based on data from an ensemble of atmospheric-ocean general circulation models (AOGCMs) used for the Intergovernmental Panel on Climate Change's (IPCC's) Fifth Assessment Report (AR5), were used to quantify potential climate change impacts on winter weather and hydrology in the study region and understand implications for its tourism sector.

New Hydrologic Insights for the Region: By the 2080s, climate change could result in winters that are shorter by over a month, reductions of over a month in days with snow depths required for many kinds of winter recreation, declines in average holiday snow depths of 50 percent or more, and reductions in the percent area of the study region that would be considered viable for winter tourism from about 22 percent to 0.3 percent. Days with temperatures suitable for artificial snowmaking decline to less than a month annually, making it potentially less feasible as an adaptation strategy. All of the region's current ski resorts are operating in areas that will become non-viable for winter tourism businesses under a high emissions scenario. Given the economic importance of the winter tourism industry in the study region, businesses and communities should consider climate change and potential adaptation strategies in their future planning and overall decision-making.

1. Introduction

Cold season hydrologic processes play an important role in shaping the physical behavior of North America's Laurentian Great Lakes. Low air temperatures have a significant impact on the formation and break-up of lake ice and, subsequently, lake dynamics in warmer months of the year (Mishra et al., 2011b). Frozen soils and seasonal freeze-thaw patterns affect infiltration, soil properties, and overall land energy balances (Cherkauer and Lettenmaier, 1999; Lemke et al., 2007). Seasonal snowpack plays an important role in surface energy and water budgets, soil temperatures, surface albedo, and evapotranspiration (Cohen and Rind, 1991; Dyer and Mote, 2006; Karl et al., 1993; Mortsch et al., 2000; Rodell and Houser, 2004; Sinha and Cherkauer, 2008). Snowpack and snowmelt runoff also affect seasonal streamflow behavior, including peak streamflow during the spring, and the development and replenishment of lakes and wetlands in the region (Mishra and Cherkauer, 2011).

Cold weather phenomena are also important to many economic sectors in the Great Lakes, especially tourism. Winter tourism is

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highly dependent on temperature, snow cover, snowfall, length of the snow season, and the presence or absence of snow during winter holidays. In recent years, desirable conditions for winter tourism are perceived to have become less reliable by Great Lakes tourism professionals (Chin, 2016). Previous research has also shown that tourism business owners are already adapting to changing conditions, for example, by offering snowshoes in lieu of cross-country skiing and adopting snowmaking to account for reductions in snowfall and snowpack (Burakowski and Magnusson, 2012; Chin, 2016; Scott et al., 2008).

Quantitative hydrologic analyses support tourism stakeholders' perceptions that winter weather has become less suitable for winter recreation in recent decades. Average winter and spring temperatures have both been increasing in the Great Lakes region, while seasonally frozen ground has been decreasing over the last century, especially in the spring (Mortsch et al., 2000; Sinha and Cherkauer, 2008). Similarly, the last spring freeze has shifted earlier in the year, leading to shorter winter seasons (Pryor, 2013; Pryor et al., 2014). The Great Lakes has also been experiencing shifts in precipitation from snow to rain, earlier annual snowmelt, and reductions in spring snow cover (Brown, 2000; Brown and Goodison, 1996; Dyer and Mote, 2006; Hodgkins et al., 2007).

Several studies have been conducted to determine how winter weather has changed in recent decades. Brown and Braaten (1998) examined changes in monthly snow depth and snow cover duration in Canada and found that both had decreased from 1946 to 1995, especially in March. Mote et al. (2005) found in their study evidence of declines in winter snowpack for western North America from 1916–2002. Durand et al. (2009) looked at daily snow depth, the number of days with snow on the ground, the maximum continuous time period with snow coverage, and minimum 100-day snow depths in the French Alps from the late 1950s to early 2000s and found a decreasing trend in snow coverage at low elevations, though this was not the case for medium to high elevations. Similarly, Hendriks et al. (2012) investigated potential changes in mean peak snow water equivalent (SWE), snow duration, fraction of precipitation as snow, and average maximum SWE in New Zealand using output from atmospheric-ocean general circulation models (AOGCMs) and found decreases in snow coverage at low elevations and, in a few cases, marginal increases at very high elevations. In addition, the Intergovernmental Panel on Climate Change's (IPCC's) Fifth Assessment Report (AR5) states that both cold temperature extremes and the amount of snow and ice have been decreasing globally since 1950 and are likely to continue to do so with future climate change (IPCC, 2014; Mote et al., 2005).

Future climate change projections for the Great Lakes region support the conclusion that changes to its winter weather and hydrology will continue and intensify (Byun and Hamlet, 2018; Winkler et al., 2014). Temperatures are expected to continue to increase, leading to reductions in cold spells and extremely cold days and further shortening winters (Hayhoe and Wubbles, 2007; Wuebbles et al., 2010). Increasing temperatures could also affect river and lake ice thickness and break-up (Bates et al., 2008). Karl et al. (1993) predict that decreases in snow cover could come in future decades as a result of temperature increases, despite some past findings that total annual snowfall will remain relatively steady (Hayhoe and Wuebbles, 2007). The redistribution of precipitation as rain versus snow could lead to higher runoff and increased flooding in the region (Byun et al., in review.; Hayhoe et al., 2010; Karl et al., 1993; Mortsch et al., 2000; Rosenzweig et al., 2002).

In terms of how these changes will affect winter tourism specifically, Scott et al. (2006, 2003), Scott and McBoyle (2007) used a snow model coupled with the Variable Infiltration Capacity (VIC) model to look at changes in snow depths appropriate for skiing and snowmobiling in the northeastern United States and Canada using climate projections from three different AOGCMs for two emissions scenarios. They found the potential for significant losses for the ski and snowmobiling industries due to declines in seasonal snowpack, though artificial snowmaking reduced some of this vulnerability. Studies by Durand et al. (2009) and Hendriks et al. (2012) also indicate the potential for economic losses, specifically for downhill ski resorts, due to decreases in snow cover duration and the amount of snow cover at elevations where these businesses typically operate. Wobus et al. (2017) recently quantified potential losses for winter recreation due to climate change as being in the hundreds of millions of dollars across the United States.

Overall, these findings suggest that, without adaptation, winter-based tourism businesses could face significant losses or even failure due to future climate change impacts on Great Lakes winter weather and hydrology. While artificial snowmaking might mitigate some decreases in snow reliability, it is a strategy that is very resource intensive, both financially and in terms of water use (Rixen et al., 2011; Steiger and Mayer, 2008). In addition, research indicates that tourists' acceptance of artificial snowmaking is equivocal (Pütz et al., 2011). Technological advances will also likely be needed for snowmaking to be effective in the future, due to current limitations on temperatures for snowmaking (usually below -2°C) (Wobus et al., 2017). Subsequently, alternative strategies need to also be considered in discussions about climate change preparedness. These findings also support the argument that winter tourism businesses need to be proactively preparing for potential changes in future cold and snow conditions in a way that takes into account a number of competing interests. Regional scale analyses of future climate projections related to winter weather can assist with these efforts.

This work builds on existing analyses by considering how climate change could impact winter weather and hydrology important to tourism for the U.S. portion of the North American Laurentian Great Lakes region. Statistically-downscaled climatic data from AOGCMs, which constitute IPCC AR5, have been used to run VIC model simulations of snow processes for this analysis. The overall objective of this study is to produce detailed information about potential climate change impacts on winter weather and hydrologic response in the Great Lakes that is directly relevant to winter recreation and tourism and that can be used to help tourism managers think about climate change and adaptation strategies for the future. In summary, the following research questions are being considered:

- 1 How will climate change affect winter conditions in the Great Lakes through the end of the century?
- 2 How could changes in winter processes affect winter recreation and tourism in the region?

2. Materials and methods

2.1. Study area

The North American Laurentian Great Lakes system is the largest freshwater system on Earth, containing about 20 percent of the global freshwater supply (Grannemann and Reeves, 2005). It is made up of five hydrologically connected lakes (Erie, Huron, Michigan, Ontario, and Superior) with a cumulative volume of roughly 22 quadrillion liters (McBean and Motiee, 2008) and a drainage area of 770,000 square km (Croley, 1990). The Great Lakes are bordered by eight U.S. states and one Canadian province. Across the Great Lakes region, average annual precipitation ranges from about 680 to 1190 mm and average temperature ranges from about -13 to -1 °C in January and $+17$ to $+23$ °C in July (Hodgkins et al., 2007).

Winter tourism added over \$3.5 billion to Great Lakes states' economies during the 2009–2010 season (Burakowski and Magnusson, 2012). The total gross annual revenue of downhill skiing and snowboarding areas in Great Lakes states is estimated at about \$1.6 billion (National Ski Areas Association, 2016). Snowmobiling adds about \$800 million annually to Michigan's economy, alone (Stoddard, 2017). Snowshoeing, snowboarding, and ice fishing are also popular forms of winter recreation. Overall, winter tourism provided close to 63,000 jobs in Great Lakes states during the 2009–2010 season (Burakowski and Magnusson, 2012).

2.2. The variable infiltration capacity (VIC) model

The VIC model is a land surface hydrology model that can be used to simulate water and energy balances for large watersheds, as well as streamflow when paired with a routing model (Gao et al., 2009; Liang et al., 1996, 1994; Lohmann et al., 1996; Wood et al., 1992). Typically, the VIC model is set up to run based on gridded locations, calculating a wide variety of output variables for each cell at the designated time step based on climate, soil, and vegetation input data. The VIC model assumes that, at the macro-scale, vertical transfers are more important than horizontal transfers in determining water and energy balances at each location at a large spatial scale, so each grid cell is simulated individually. Daily meteorological data is provided to the VIC model for, at least, daily precipitation, maximum and minimum temperature, and average wind speed for each grid cell, which was the time step used for the simulations in this study. The model is also able to handle sub-daily meteorological information, and the energy balance snow model is typically (as here) run at an hourly time step (Andreadis et al., 2009).

In this study, output from a series of VIC model simulations was used to quantify changes in cold processes and determine the potential impacts of climate change on winter weather in the Great Lakes. The VIC model determines changes in snow conditions using the energy balance for each individual grid cell. Snowpack is represented using a two-layer scheme with energy exchange occurring only at the surface (Andreadis et al., 2009; Gao et al., 2009). For these simulations, changes in the density of snowpack were calculated based on an algorithm developed from typical monthly snow density measurements (Bras, 1990), while snow albedo was determined according to a U.S. Army Corps of Engineers algorithm (Gao et al., 2009). Minimum (-0.5 °C) and maximum temperature ($+2$ °C) thresholds for rain and snow, respectively, determine the form in which precipitation falls.

The VIC model has been used in several different studies to examine cold processes in the Great Lakes, especially its western region. Sinha et al. (2010) used the VIC model to examine the effects of historical climate variability on soil frost, soil temperature, and snow water equivalent in the Great Lakes, while Mishra et al. (2011a) and Mishra et al. (2011b) used the VIC model to examine historical trends in lake ice phenology. Mishra and Cherkauer (2011) also used the VIC model to consider the role of cold season

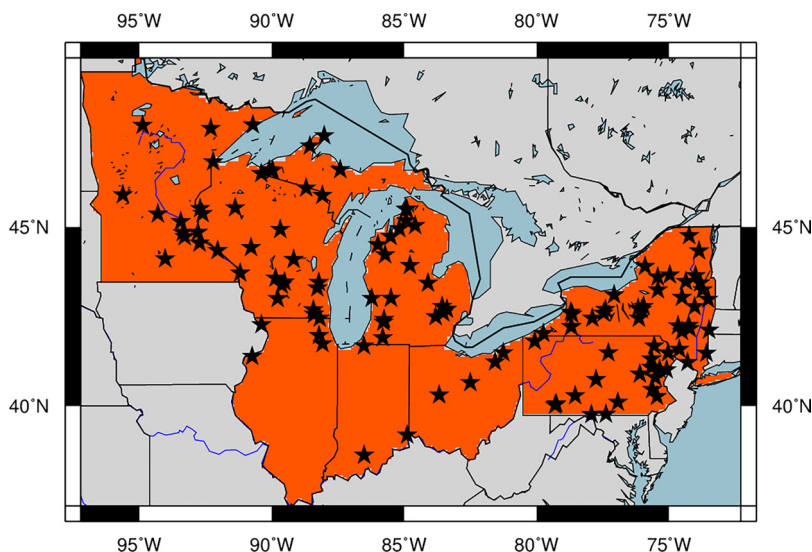


Fig. 1. Study Region (stars indicate current locations of ski resorts) (OnTheSnow, 2018).

Table 1
AOGMCs Used and Modeling Center (or Group) Providing Model Output.

AOGCM	Modeling Center (or Group)
CESM1-CAM5	National Center for Atmospheric Research, USA
FIO-ESM	The First Institute of Oceanography, SOA, China
GFDL-CM3	NOAA Geophysical Fluid Dynamics Laboratory, USA
GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory, USA
HadGEM2-AO	National Institute of Meteorological Research/Korea Meteorological Administration, South Korea
HadGEM2-CC	Met Office Hadley Center, UK

climate extremes and variability on the inundation extent of lakes and wetlands based on historical trends.

For this study, the VIC model was set up to include U.S. states around the Great Lakes at a $1/16^\circ$ grid cell resolution (Fig. 1). Three soil layers were defined for this iteration of the model with soil properties for each grid cell being extracted from the 1998 CONUS-SOIL dataset (Livneh et al., 2014; Miller and White, 1998). A total of eleven land cover types were defined for the model simulations. Land cover fractions for each grid cell were determined using data from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) with the International Geosphere-Biosphere Programme's (IGBP's) global vegetation classification scheme, as measured in 2000 (Hansen et al., 2000; Livneh et al., 2014).

2.3. Selection of VIC model climate forcing data

Climate data from the World Climate Research Programme's Coupled Model Intercomparison Program phase 5 (CMIP5) was used to run VIC model simulations for this study. The CMIP5 dataset is comprised of an ensemble of climate models produced through a coordinated effort by research groups around the world with the aim of meeting the most major priorities of user communities (see Taylor et al. (2012) for additional details).

Output from an ensemble of CMIP5 model runs was statistically-downscaled using the Hybrid Delta (HD) method (Hamlet et al., 2013), as described in Byun and Hamlet (2018) and used to analyze climate change impacts for the study region. RegridDED historical daily precipitation, maximum surface air temperature, and minimum surface air temperature measurements covering the United States portion of the Great Lakes region for 1915–2013 were adjusted based on monthly temperature and precipitation averages calculated from the ensemble of CMIP5 model runs (Byun and Hamlet, 2018; Chiu et al., in review). The full set of AOGCMs used, which were selected based on satisfactory representation of historical Midwest climate and to include models that best represent the central tendency and outermost range of possible climate futures, is shown in Table 1. The daily wind data used is based on daily climatology (pre-1950) and National Center for Atmospheric Research (NCAR) Reanalysis simulations (post-1950) (Chiu et al., in review). Two representative concentration pathways, RCP 4.5 and RCP 8.5, were analyzed to understand the effects of medium-low and high levels of carbon dioxide concentrations (Byun and Hamlet, 2018; Moss et al., 2010).

Extensive calibration and validation of the model in terms of its simulation of cold and snow processes was outside the scope of this study; however, the model has been evaluated based on its ability to simulate streamflow in 40 different watersheds (Chiu et al., in review). As part of this analysis, a gauge undercatch correction was applied to the meteorological forcing data because of apparent issues with snowfall measurements, resulting in good model performance. In general, the VIC model has been shown to do well at simulating snow (Andreadis et al., 2009).

2.4. Selection of metrics

A review of existing literature determined the metrics used to evaluate the potential impacts of climate change on winter weather and hydrology and associated impacts on the tourism sector for this study. Based on work by the CCI/CLIVAR/JCOMM Expert Team (ET) on Climate Change Detection and Indices (ETCCDI) (Zhang, 2013), length of winter, or the number of days between the first and last occurrence of at least 6 days with a daily average temperature of less than $+5^\circ\text{C}$, was selected as one of the metrics. Cold days, or the number of days where the maximum daily temperature is below -5°C , was also used to further explore how winter weather might change in the future.

Additional metrics were determined based on a review of existing studies looking specifically at climate change and winter tourism. Scott et al. (2008) defined favorable conditions for downhill skiing as a snow depth of 30 cm and for snowmobiling as a snow depth of 15 cm with a maximum daily temperature of less than $+15^\circ\text{C}$ and a 2-day precipitation total of less than 20 mm. Kundzewicz et al. (2008), on the other hand, defined appropriate snow depths for snowboarding as 30 cm and for downhill skiing as 40 cm. Here, the Kundzewicz et al. metric (40 cm) was used to look at days for downhill skiing because Scott et al. included snowmaking in their analysis. Snowmaking has not been incorporated into the VIC model simulations completed for this work, so metrics accounting for it were deemed inappropriate for this application; however, the number of days with temperatures required for artificial snowmaking (i.e. the number of days where the maximum daily temperature is less than -2°C) was used to determine how climate change could affect the ability of winter tourism businesses to use this practice in the future (Wobus et al., 2017). A snow depth of 15 cm was used to determine the number of days appropriate for snowmobiling. This depth also reflects the number of days that would be conducive to other types of winter recreation like snowshoeing and cross-country skiing.

Finally, three additional criteria were used to evaluate climate change impacts on winter tourism: (1) viable areas for downhill ski

Table 2
List of Metrics Used for Analysis.

Variable	Definition
Length of Winter	Number of days between the first and last occurrence of at least 6 days with a daily average temperature of less than +5 °C
Cold Days	Number of days where the maximum daily temperature is below −5 °C
Days for Downhill Skiing	Number of days with a snow depth of 40 cm or more
Days for Snowmobiling	Number of days with a snow depth of 15 cm or more
Days with Temperatures Required for Artificial Snowmaking	Number of days where the maximum daily temperature is less than −2 °C
Viable Areas for Downhill Ski Resorts	Areas with snow depths of at least 30 cm for over 100 days during the year
Viable Areas for Other Winter Tourism Businesses	Areas with snow depths of at least 15 cm for over 100 days during the year
Average Holiday Snow Depths	Average daily snow depths from December 22 to January 2

resorts, defined as areas with snow depths of at least 30 cm for over 100 days during the year, (2) viable areas for other types of winter tourism businesses, defined as areas with snow depths of at least 15 cm for over 100 days during the year, and (3) average holiday snow depths, defined as the average daily snow depth from December 22 to January 2 (Durand et al., 2009; Scott et al., 2008). The full set of metrics used in this analysis is summarized in Table 2.

Thirty-year averages for a relative time period of 1980–2010 were calculated and compared for each metric. These averages were calculated by first finding the 30-year average for each grid cell and then computing a spatial average for the entire model domain. A year was defined as being from July 1 of the previous year to June 30 of the current year to ensure that the entire winter season was captured in a single year. The near future period is based on climate projections for a 30-year window centered on the 2020s (2011–2040); the mid future period on climate projections for the 2050s (2041–2070); and the far future period on climate projections for the 2080s (2071–2100), respectively.

The results of this analysis are presented in the following section. Historical maps of 30-year averages are based on VIC simulations forced by gridded observational data for the study domain. Maps of future 30-year averages are based on mean values calculated from VIC simulations forced by the set of six downscaled AOGCMs (Byun and Hamlet, 2018). State names are abbreviated as follows: Illinois - IL, Indiana - IN, Michigan - MI, Minnesota - MN, New York - NY, Ohio - OH, Pennsylvania - PA, and Wisconsin - WI.

3. Results and discussion

Historical (1980–2010) 30-year spatial averages for the full study domain of each of the metrics selected for this analysis are listed in Table 3. The winter season has historically averaged close to 5 months across the study region with a little over 3 weeks of cold days, as previously defined. Days with appropriate snow depths for downhill skiing have averaged about 4 weeks and days with appropriate snow depths for snowmobiling have averaged about 8 1/2 weeks annually. A little over 2 months each year, on average, have had temperatures suitable for artificial snowmaking. For historical conditions, close to 9 percent of the study region would be considered viable for downhill ski resorts and close to 23 percent viable for other types of winter tourism businesses. Holiday snow depths have averaged about 18.6 cm across the study region.

The first metric considered is *length of winter*. As shown in Table 4, the ensemble of AOGCMs predicts that the length of winter will decrease from the historical to the future periods for the entire domain and each state. The reduction in the near future period is around 2 weeks, mid future period about 3 weeks, and far future period about a month or more for both RCPs.

Plots illustrating spatial patterns for the length of winter across the Great Lakes region are shown in Fig. 2. As seen in Fig. 2(a), the historical average for the length of winter for the study region ranges from around 70 days in the southern portion of the study region to over 200 days in the northern portion of the study region. Plots of 30-year averages for the future periods (Fig. 2,(b)–(g)) show that the greatest decreases in the length of winter generally occur in the most northern parts of the study region, likely due to a greater sensitivity to climate change at higher latitudes (Byun and Hamlet, 2018). These decreases are around 3–4 weeks in the near future period (Fig. 2,(b) and (e)); 5–6 weeks in the mid future period (Fig. 2,(c) and (f)); and 6–10 weeks in the far future period (Fig. 2,(d)

Table 3
: Historical 30-Year Spatial Averages of Each Metric for the Full Study Domain.

Variable	30-Year Average
Length of Winter	143 days
Cold Days	23 days
Days for Downhill Skiing	28 days
Days for Snowmobiling	61 days
Days with Temperatures Required for Artificial Snowmaking	39 days
Viable Areas for Downhill Ski Resorts	8.7%
Viable Areas for Other Winter Tourism Businesses	22.7%
Average Holiday Snow Depth	18.6 cm

Table 4
30-Year Averages for Length of Winter (in days).

			Location								
			Entire Domain	IL	IN	MI	MN	NY	OH	PA	WI
Time Period	Historical		143	115	116	154	166	149	120	132	158
	RCP 4.5	Near Future	130	103	104	140	155	135	109	120	145
		Mid Future	124	94	96	134	149	128	102	114	139
		Far Future	119	90	92	129	144	124	98	109	134
	RCP 8.5	Near Future	131	104	105	140	156	136	109	121	146
		Mid Future	118	89	91	128	143	123	96	108	134
		Far Future	100	70	72	108	127	104	77	89	116

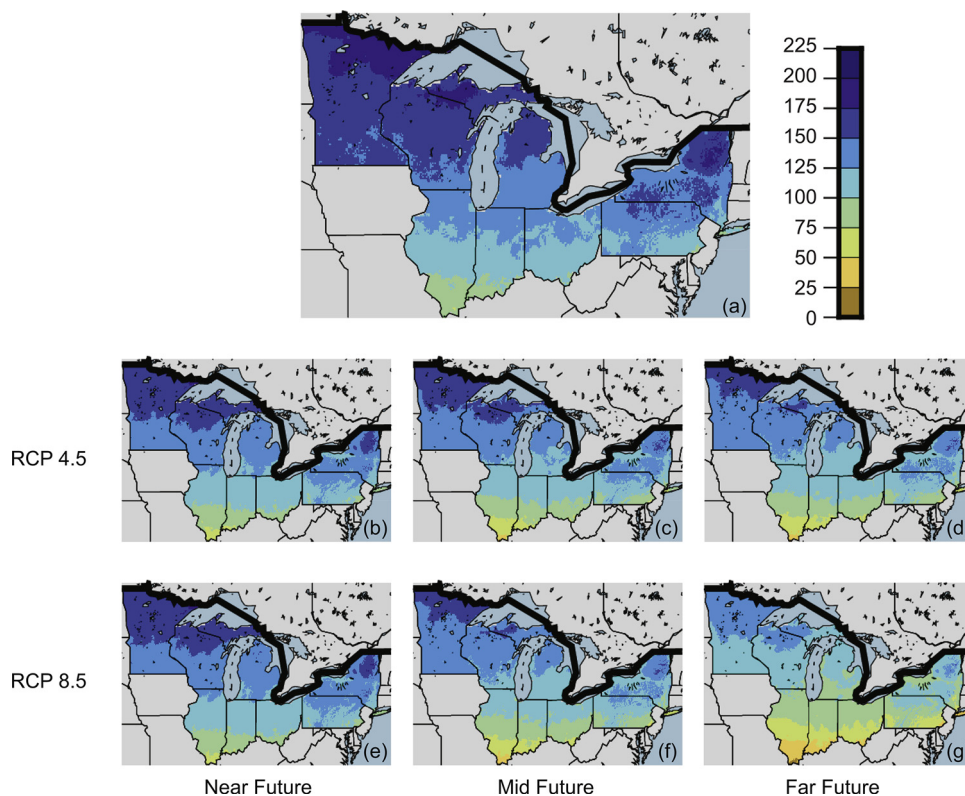


Fig. 2. 30-Year Averages for Length of Winter (in days): (a) Historical (1980–2010) 30-Year Average, (b)–(g) Future 30-Year Averages.

and (g)).

Table 5 shows analysis results for *cold days*. Similar to *length of winter*, the ensemble of AOGCMs predicts that the number of cold days annually will decrease from the historical to the future periods. Reductions range from a few days to a few weeks through the

Table 5
30-Year Averages for Cold Days (in days).

			Location								
			Entire Domain	IL	IN	MI	MN	NY	OH	PA	WI
Time Period	Historical		23	10	9	21	47	19	8	9	32
	RCP 4.5	Near Future	15	6	5	13	32	12	5	5	21
		Mid Future	12	5	4	10	28	9	3	4	17
		Far Future	12	4	4	10	27	9	3	4	16
	RCP 8.5	Near Future	15	6	5	12	33	11	4	5	20
		Mid Future	10	4	3	8	25	8	3	3	14
		Far Future	7	2	2	5	17	5	1	2	9

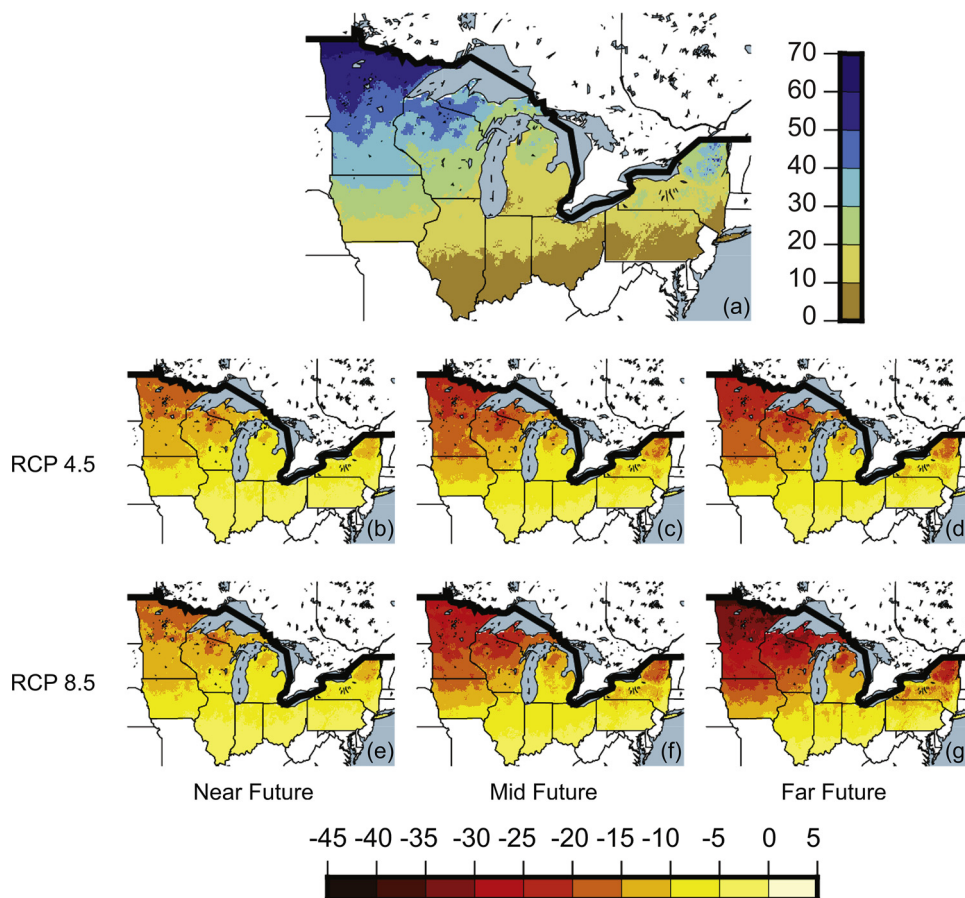


Fig. 3. 30-Year Averages for Cold Days: (a) Historical (1980–2010) 30-Year Average, (b)–(g) Future 30-Year Averages.

end of the century.

Spatial plots for the number of cold days also show similar spatial patterns to those found for *length of winter* (Fig. 3). The greatest reductions in the number of cold days occur in the northern part of the study region, with the number of days declining by over a month.

In terms of *days for downhill skiing* and *days for snowmobiling*, the VIC model simulations predict a decrease in the number of days with appropriate snow depths for both activities (Tables 6 and 7), reflecting the significant decrease, overall, in snow depths for the study region through the end of the century as a result of climate change. The AOGCMs predict a decrease of up to 19 days for downhill skiing and 21 days for snowmobiling in the near future, a decrease of up to 26 days and 21 days in the mid future, and a decrease of up to 33 days and 38 days in the far future for RCP 4.5. For RCP 8.5, decreases of 19 and 23 are predicted for the near future, 37 and 47 for the mid future, and 50 and 62 for the far future for downhill skiing and snowmobiling, respectively. New York generally experiences the greatest reductions in the number of days for downhill skiing and Wisconsin generally experiences the greatest reductions in the number of days for snowmobiling.

Figs. 4 and 5, top, show the historical 30-year averages for days for downhill skiing and snowmobiling, respectively. The areas

Table 6
30-Year Averages for Days for Downhill Skiing (in days).

			Location								
			Entire Domain	IL	IN	MI	MN	NY	OH	PA	WI
Time Period	Historical		28	2	2	48	26	68	3	30	37
	RCP 4.5	Near Future	18	0	1	4	15	50	1	18	21
		Mid Future	14	0	0	25	12	42	1	14	13
		Far Future	13	0	0	24	11	36	0	11	13
	RCP 8.5	Near Future	18	0	0	33	17	49	1	17	21
		Mid Future	10	0	0	18	8	31	0	9	8
		Far Future	5	0	0	10	4	18	0	4	4

Table 7
30-Year Averages for Days for Snowmobiling (in days).

			Location								
			Entire Domain	IL	IN	MI	MN	NY	OH	PA	WI
Time Period	Historical		61	16	16	85	75	101	18	60	82
	RCP 4.5	Near Future	46	9	10	67	58	82	11	44	61
		Mid Future	38	5	7	55	49	72	8	37	46
		Far Future	35	5	6	52	46	65	7	32	44
	RCP 8.5	Near Future	46	8	9	66	60	81	11	43	59
		Mid Future	30	4	5	44	39	59	6	28	35
		Far Future	19	2	3	27	25	39	3	18	21

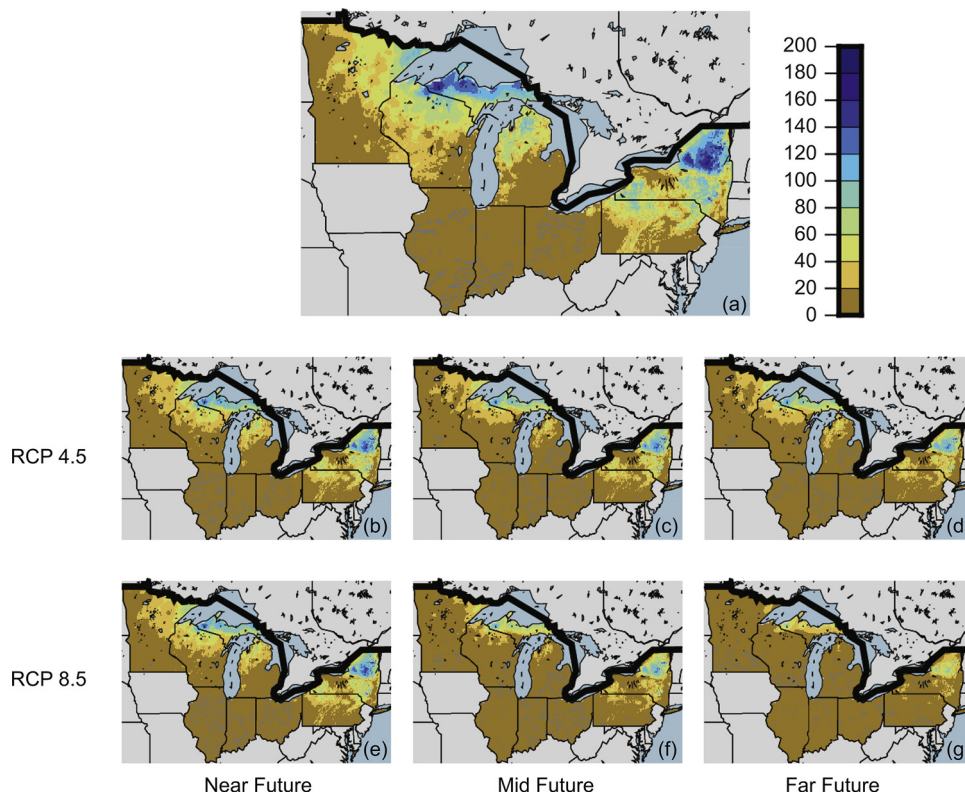


Fig. 4. 30-Year Averages for Days for Skiing (in days): (a) Historical (1980–2010) 30-Year Average, (b)–(g) Future 30-Year Averages.

with the greatest number of days with appropriate snow depths for both activities are concentrated in areas with higher elevations and around the lakes, averaging about 6 months annually in peak locations.

For both RCP 4.5 and RCP 8.5, the number of days for downhill skiing and snowmobiling across most of the southern part of the study region decreases to zero through the 2080s. In areas that historically experience more days with appropriate snow depths for downhill skiing and snowmobiling, the decrease in the number of days is more severe, with declines of about 1–2 months through the end of the century. Analysis by (Byun and Hamlet, 2018) shows that these steep reductions in snow depths are caused by more precipitation falling as rain rather than snow due to rising temperatures.

In terms of *days with temperatures required for artificial snowmaking*, the ensemble of AOGCMs predicts a decrease in the number of days in the future (Table 8). Declines are similar to those seen with other metrics, ranging from about a week in the near future to about a month in the far future under both RCPs.

As shown in Fig. 6, reductions in the number of days with temperatures required for artificial snowmaking are greatest in the northern part of the study region, which corresponds to the region where this practice is also most likely to be used to try and offset losses in reliable snow cover and winter weather. In northern Minnesota and New York, the number of days with temperatures suitable for artificial snowmaking could decrease by 50 percent or more in the far future.

The simulation results also show that *viable areas for downhill ski resorts* and *viable areas for other winter tourism businesses* will decline in spatial extent due to reductions in overall snow depths as a result of climate change (Table 9 and 10). While only about 8.7

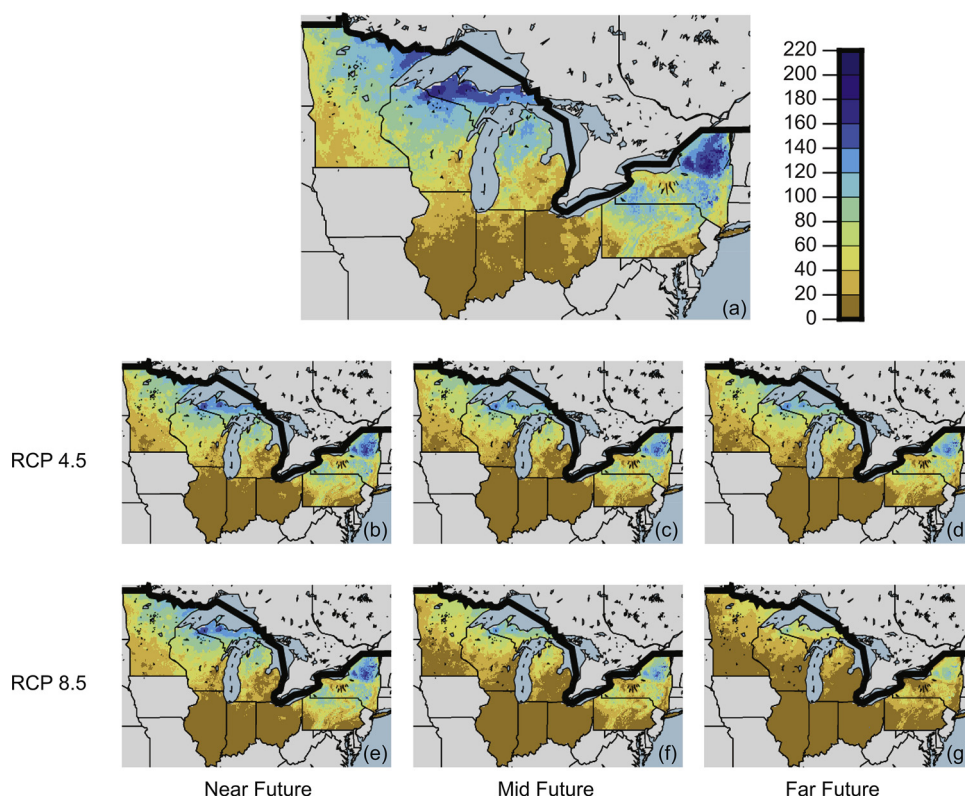


Fig. 5. 30-Year Averages for Days for Snowmobiling (in days): (a) Historical (1980–2010) 30-Year Average, (b)–(g) Future 30-Year Averages.

Table 8

30-Year Averages for Days with Temperatures Required for Artificial Snowmaking (in days).

			Location								
			Entire Domain	IL	IN	MI	MN	NY	OH	PA	WI
Time Period	Historical		39	20	18	41	68	36	19	21	52
	RCP 4.5	Near Future	31	14	13	32	57	28	13	16	42
		Mid Future	26	11	10	26	50	23	10	12	35
		Far Future	24	11	9	24	47	21	9	11	33
	RCP 8.5	Near Future	31	14	12	32	58	28	13	15	42
		Mid Future	22	10	9	22	44	20	8	10	30
		Far Future	15	6	5	13	32	13	5	6	20

percent of the study region would be considered viable for downhill ski resorts historically (Table 3), it is possible that essentially the entire region will experience less than 100 days of at least 30 cm of snow on an annual basis. Similar declines are also predicted in terms of the viable area for other types of winter tourism businesses.

Fig. 7 shows the spatial distribution of viable areas for downhill ski resorts and other winter tourism businesses. Once again, these areas are concentrated at higher elevations and around the lakes. When considered in conjunction with the current locations of ski resorts, these results suggest that only 80 of 122 businesses are currently operating in areas that are would be historically classified as viable for downhill ski resorts and other winter tourism businesses. In addition, all current ski resorts are operating in areas that will become non-viable based on RCP 8.5 by the 2080s.

Average holiday snow depths are also predicted to decline in the future (Table 11). In addition to declines in average daily holiday snow depths of half or more through the end of the century, only New York will have holiday snow depths of over 15 cm (the threshold used to determine the number of days with appropriate snow cover for snowmobiling and other types of winter tourism activities) at the end of the century under RCP 4.5, and no states will experience depths of over 15 cm under RCP 8.5 for the mid future and far future periods.

Fig. 8 shows historical and future 30-year averages for holiday snow depths across the study region. Similar to the previous snow depth-related variables, areas with the highest averages for holiday snow depths are concentrated at higher elevations and around the lakes. The greatest declines occur in areas in the northern part of the study domain that historically experience colder weather and

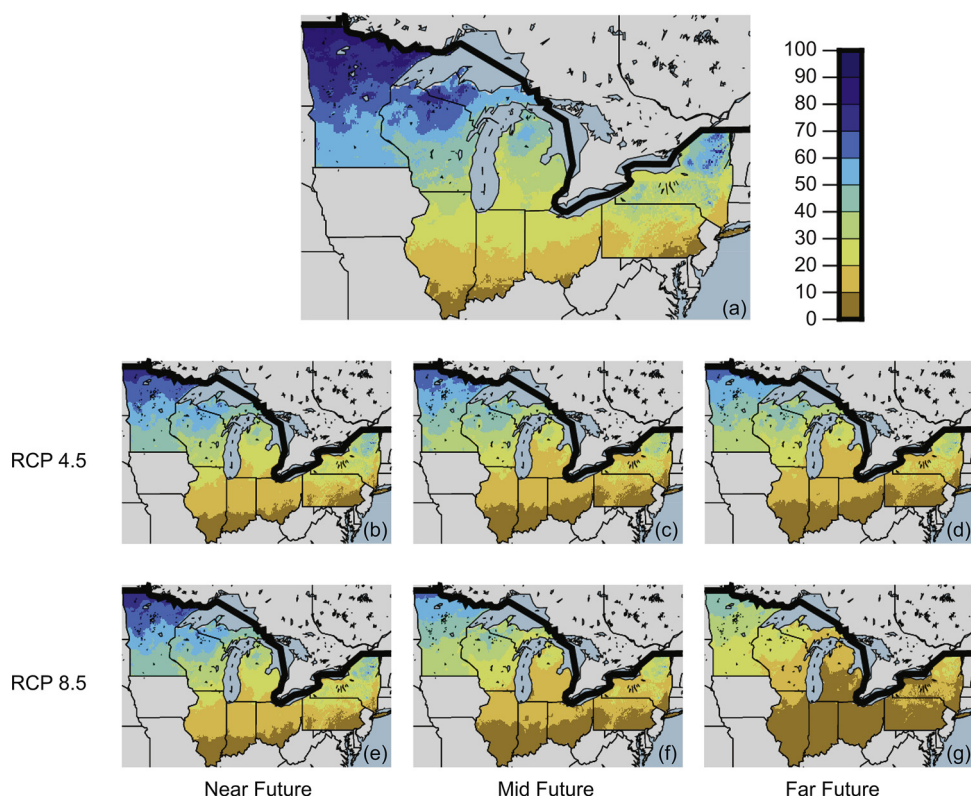


Fig. 6. 30-Year Averages for Days with Temperatures Required for Artificial Snowmaking: (a) Historical (1980–2010) 30-Year Average, (b)–(g) Future 30-Year Averages.

Table 9

30-Year Averages for Percent Viable Area for Downhill Ski Resorts.

			Location								
			Entire Domain	IL	IN	MI	MN	NY	OH	PA	WI
Time Period	Historical		8.7	0.0	0.0	24.4	4.0	33.1	0.0	1.3	4.8
	RCP 4.5	Near Future	4.2	0.0	0.0	13.8	0.6	18.3	0.0	0.0	0.9
		Mid Future	2.3	0.0	0.0	6.0	0.1	12.3	0.0	0.0	0.4
		Far Future	1.4	0.0	0.0	3.4	0.0	8.1	0.0	0.0	0.2
	RCP 8.5	Near Future	4.1	0.0	0.0	13.5	0.7	17.5	0.0	0.0	0.9
		Mid Future	0.8	0.0	0.0	1.3	0.0	5.4	0.0	0.0	0.0
		Far Future	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0

Table 10

30-Year Averages for Percent Viable Area for Other Winter Tourism Businesses.

			Location								
			Entire Domain	IL	IN	MI	MN	NY	OH	PA	WI
Time Period	Historical		22.7	0.0	0.0	43.0	26.9	56.0	0.0	12.1	27.1
	RCP 4.5	Near Future	10.1	0.0	0.0	26.3	9.0	31.5	0.0	1.5	7.2
		Mid Future	6.3	0.0	0.0	19.1	3.9	23.1	0.0	0.3	1.8
		Far Future	4.6	0.0	0.0	14.8	2.5	16.9	0.0	0.0	1.2
	RCP 8.5	Near Future	10.3	0.0	0.0	25.8	11.0	30.5	0.0	1.4	6.8
		Mid Future	2.7	0.0	0.0	8.0	0.4	12.4	0.0	0.0	0.7
		Far Future	0.3	0.0	0.0	0.4	0.0	1.8	0.0	0.0	0.0

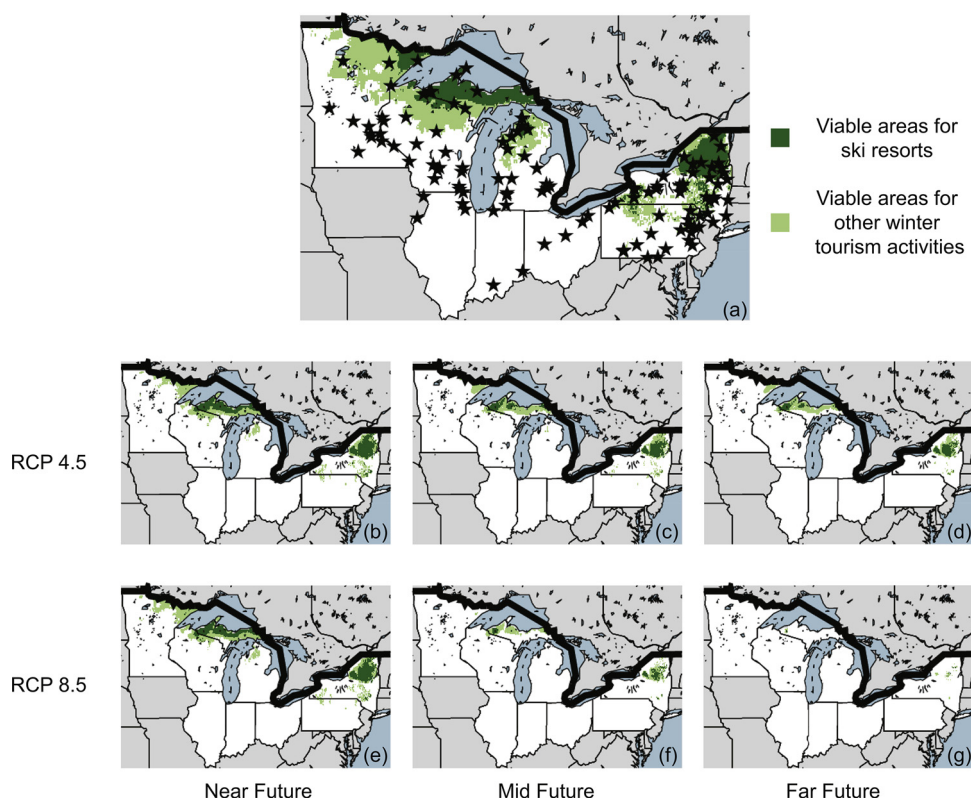


Fig. 7. Viable Winter Tourism Areas: (a) Historical (1980–2010, stars indicate current locations of ski resorts), (b)–(g) Future Periods.

Table 11

30-Year Averages for Holiday Snow Depths (in cm).

			Location								
			Entire Domain	IL	IN	MI	MN	NY	OH	PA	WI
Time Period	Historical		18.6	7.1	7.0	25.9	21.4	32.3	5.9	15.8	24.1
	RCP 4.5	Near Future	12.1	3.6	3.9	17.3	15.4	21.1	3.2	9.3	15.8
		Mid Future	10.2	2.8	3.2	14.0	13.6	18.7	2.7	7.8	12.6
		Far Future	9.0	2.4	2.6	12.7	11.9	16.4	2.3	6.8	11.1
	RCP 8.5	Near Future	12.3	3.7	4.0	17.5	15.7	21.3	3.3	9.3	15.9
		Mid Future	7.8	2.1	2.2	10.6	10.7	14.2	1.9	5.5	9.4
		Far Future	5.4	1.6	1.7	7.4	8.0	8.9	1.3	3.3	6.8

also currently support ski resorts.

Overall, these results demonstrate that changes to the study region's winter weather and hydrology will significantly affect its ability to support winter tourism by the end of the century.

4. Discussion and conclusions

The AOGCMs analyzed in this study predict that cold weather and associated cold processes in the Great Lakes region could decline substantially by the end of the century as a result of climate change. In general, winter weather, both in terms of cold temperatures and snow cover, will decline significantly in the study region, which will have significant impacts on the region's hydrologic processes, as shown through shorter winters, fewer cold days, and steep declines in snow depths. These impacts, in turn, are expected to have serious implications for local winter tourism businesses.

The decrease in the length of winter presents obvious problems for the long-term sustainability of winter tourism businesses, as revenues will need to be made during timeframes that are shortened by over a month. Businesses may be able to compensate for some shortening of their operating seasons by hiring fewer staff or planning to open and close at later or earlier dates, respectively; however, this would also likely stifle business growth and affect communities that are reliant on winter tourism over time (Gilaberte-Búrdalo et al., 2014). Instead, increasing operations in the shoulder seasons, such as opening up trails and slopes to mountain biking,

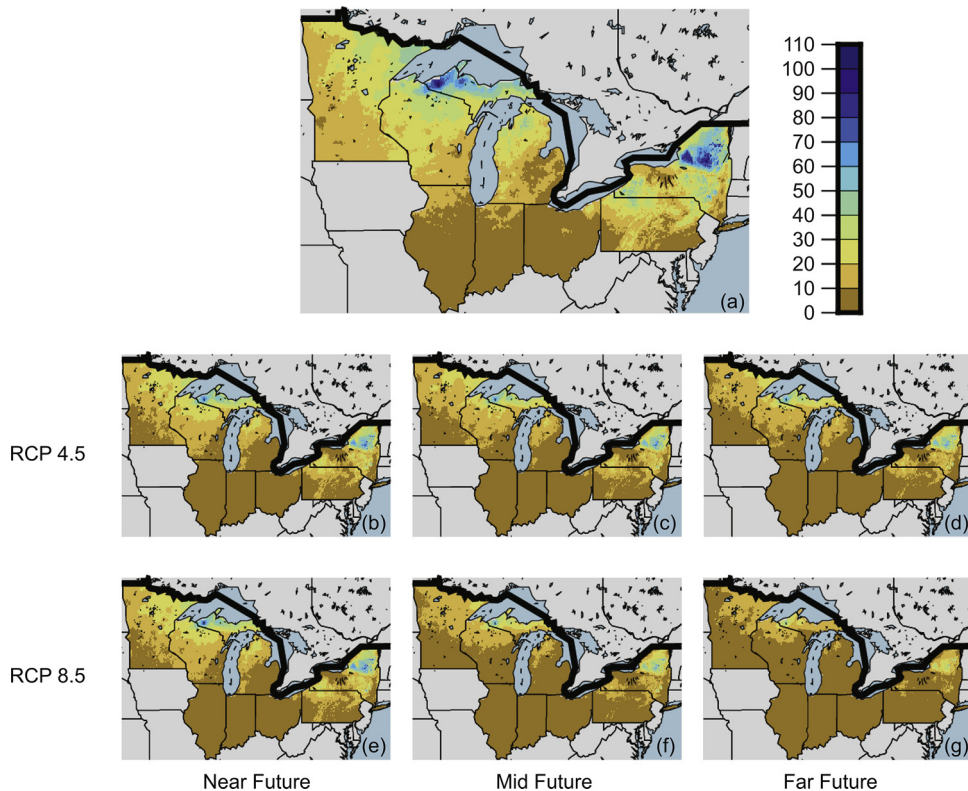


Fig. 8. 30-Year Average for Total Holiday Snow Depths (in cm): (a) Historical (1980–2010) 30-Year Average, (b)–(g) Future 30-Year Averages.

may be a more effective approach.

Reductions in the number of cold days would have similar effects on winter tourism businesses, but a gradual warming in the winter months, at least in the short term, could encourage customers to engage more in outdoor activities in the winter, if there is still adequate snow cover for other recreational opportunities like snowshoeing and cross-country skiing. Over the long term, however, the reduction in the number of cold days to a week or less per year is likely to drive tourists further northward, if they want to engage in winter recreation. Business operators will have to be cognizant of changing patterns in winter weather and ready to adapt as conditions change. For example, transportation to recreation areas may improve due to reduced snow, providing additional opportunities to generate revenue if businesses can bring in customers for alternate winter activities.

When it comes to the number of days for downhill skiing and snowmobiling, the AOGCMs predict that the number of days appropriate for both activities could decline by a few weeks to over a month in the Great Lakes region for both RCP 4.5 and RCP 8.5 by the 2080s. Supporting analysis shows that overall snowfall will decline due to rising temperatures and the resulting conversion of precipitation from snow to rain (Byun and Hamlet, 2018). These losses will likely require more drastic action from skiing and snowmobiling-related businesses, as well as other nature-based winter tourism businesses, to make up for lost revenue from the reduction in reliable snow cover, such as a diversification of winter offerings, an expansion of summer operations, or an increased reliance on artificial snowmaking.

For artificial snowmaking, however, these results show that the number of days with temperatures required for this practice to be used also decreases in the future, to less than a month annually. Technological advancements may be able to deal with some of the reductions in the number of days that artificial snowmaking can be used, but it is unlikely to be able to account for the full extent of losses in terms of snow cover, especially over the long term. In addition, the costs of artificial snowmaking will rise as natural snow cover continues to decline, forcing business owners to balance costs against their profit margin (Damm et al., 2014). However, available water will likely increase by the 2080s, so water supplies may support additional artificial snowmaking if it remains cost effective.

The percent of viable area for downhill ski resorts declines to close to zero by the end of the century. Average holiday snow depths are also predicted to decline by half or more by the end of the century. This is key for winter tourism in the Great Lakes region because these variables have been shown to be important indicators of business viability. Similar declines are seen in the percent of viable area for other types of winter tourism businesses. In addition, the areas with the greatest declines in these variables also correspond with current locations of ski resorts in the Great Lakes. Over the long-term, this could result in business closure or relocation. Grooming of slopes may help to reduce the amount of snow required to safely operate downhill ski areas, however, this practice may also become ineffective as temperatures rise and snow cover declines over time.

While an in-depth economic analysis was not within the scope of this study, the results of previous work can provide some

indication of the potential economic impacts of climate change on winter tourism in the Great Lakes states. For the states in the northern portion of the study region and the ones most impacted by declines in winter weather, winter tourism added about \$506 billion to the economy, in the case of Minnesota, to about \$845 billion, in the case of New York, during the 2009–2010 season (Burakowski and Magnusson, 2012). In addition, when comparing skier visits in the five years with the most snow with the five years with the least snow from 2001 to 2016, Hagenstad et al. (2018) found that low snow years resulted in declines in patronage and seasonal revenue for all eight states in the study region. Given these findings, it is evident that declines in weather conditions conducive to winter tourism could have significant impacts on the economies of these eight states.

Overall, these results imply that certain states in the Great Lakes, like Michigan and New York, could experience significant losses in terms of reliable snow cover for winter tourism and recreation by the middle of the century due to climate change effects on regional weather and hydrology. These results are similar to those found in existing research, though the declines in winter weather are more extreme for some areas than those predicted by other AOGCMs and snow models (Scott et al., 2008; Wobus et al., 2017). For example, in their analysis of the Northeast winter recreation tourism sector, Scott et al. (2008) found that only western New York became nonviable for winter tourism through the end of the century. Regardless, declines in winter weather and hydrology are projected to have major impacts on winter tourism throughout the Great Lakes.

5. Future research

As previously discussed, the results of this work suggest that the impacts of climate change on winter weather and hydrology could be significant for winter tourism businesses in the Great Lakes, requiring action to prepare for the future. While there are some businesses that are already adapting to perceived reductions in the reliability of winter weather in the Great Lakes, it is often difficult for tourism businesses to plan for the long term, as they operate on relatively short timescales. This analysis provides information that could be useful to tourism business owners in terms of preparing for climate change, as it provides information that can be easily summarized for different locations and quantifies changes in winter weather and hydrology that are directly relevant to winter tourism. Additionally, while the results of this study are presented in the context of winter tourism, changes to the region's overall winter weather and hydrologic patterns will have implications that extend to other economic, environmental and social areas.

There are a few important limitations of this study. First, AOGCM-driven climate data cannot fully represent small-scale storms, such as those that occur at the sub grid-cell scale, including localized precipitation events, which may impact snow process on the ground. Also, the vegetation parameters used for the VIC model simulations in this work are stationary, so they do not capture possible changes in hydrologic physical responses in the future caused by land use change, for example. Given the predicted +8 °C increase in temperature at the end of the century, it cannot be expected that the natural ecosystem will remain the same in some areas of the study domain in the future. The interpretation of these results for decision-making should take into account these potential limitations.

There are a number of directions in which this work could continue. When it comes to input data from the AOGCMs, additional work to calibrate and validate the model for the study region could improve the reliability of these projections and ensure that they are realistically simulating cold processes, for example, by validating snow model and precipitation amounts resulting from undercatch corrections to the historical climate data. Another next step for this analysis would be to incorporate artificial snowmaking into VIC model simulations, as done by Scott et al. (2008), or to use the model to assess potential changes in processes that are important to other forms of winter recreation and tourism activities, such as ice cover for ice fishing.

When considering how climate change could impact tourism businesses, further exploring how changes in winter weather directly relate to economic revenue and cost-benefit analyses of different adaptation options would be useful, such as Wobus et al.'s (2017) and Hagenstad et al.'s (2018) studies considering specific measures of revenue associated with winter tourism. This would include quantifying in greater depth the value of other winter activities like ice fishing and snowshoeing as well as additional revenue that could be generated from the expansion of spring and fall (shoulder season) activities. Similarly, an expanded, in-depth assessment of how climate change could impact tourism communities that are reliant on winter tourism and recreation in the Great Lakes could provide important insights for the region's policymakers. Research focused on the feasibility and acceptability of different adaptation options as well as the potential impact of climate change on tourists' perceptions and behaviors around winter tourism and recreation in the Great Lakes would also help improve understanding of how climate change could affect the competitive advantage of popular winter destinations in the region, for example, building on Rutty et al.'s (2017) study of recent adaptations by the ski industry to relatively poor winter conditions. Further work, in cooperation with winter tourism business owners, could also help with the assessment and evaluation of different types of adaptation strategies that could keep businesses viable with climate change (Gilaberte-Búrdalo et al., 2014).

Furthermore, expanding the scope of this study to consider how changes in winter weather and hydrology might affect the region more broadly would be beneficial to understanding greater implications for water policy and management. While the Great Lakes region has and will continue to be water-rich, climate change impacts on winter weather and hydrologic patterns will have broader implications for the region's water supplies and potentially increase conflict between users at different times of the year. Policymakers may be forced to regulate the use of water resources between different sectors. Proactive planning and consideration of how these patterns may change over time will allow for some consideration of how to move forward as the climate continues to change.

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